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Casing Failures in Cyclic Steam Injection Wells

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Abstract

Casing failure rate is high in steam injection wells and especially in cyclic steam injection wells. The high casing failure rate in such wells is related to the high casing temperature elevation from steam injection. Casing failures varies from casing ID restriction (including buckling and/or collapse) to casing parted (including leak and/or hole). This paper presents a modeling and analysis on casing temperature elevation, casing thermal stress/strain, and casing failure mechanisms in steam injection wells, with comparing with previous casing failure field-data from a Chevron steam injection project. It shows that high thermal axial compressive stress/strain can cause casing hot-yield and is attributed to casing ID restriction (including buckling and/or collapse), and high thermal axial compressive-tensile stress/strain alternation in cyclic steam injection can cause casing fatigue and is attributed to casing parted (including leak and/or hole).

Casing strain-based design seems needed for steam injection wells to take into consideration of casing hot-yield due to high thermal axial compressive stress/strain and casing thermal axial compressive-tensile stress/strain alternation on cyclic steam injection operation. Casing hot-yield and fatigue analysis approach presented in this paper may be used on casing strain-base design for steam injection wells to reduce casing failures, with selecting proper casing grade and weight to reduce casing hot-yield and casing fatigue.

Introduction

Chevron operates in many heavy-oil fields worldwide, and production casing failure is a concern on steam injection operations in these fields. This paper presents modeling and analysis on casing temperature, thermal stress/strain, and casing failure mechanism in steam injection wells, and compares with previous casing failure data from Chevron's Bakersfield Cymric 1Y steam injection project. Recommendations on casing design in steam injection wells are made, which have been used in Chevron's steam injection projects with good results.

Figure 1 shows the number of cumulative casing failure wells vs. the number of total wells in Cymric 1Y steam injection project from 1992 (the starting of Cymric 1Y project) to 2002, where the casing failure rate was about 19%, with casing failures being occurred in 69 wells out of total 370 wells completed and operated in that period.

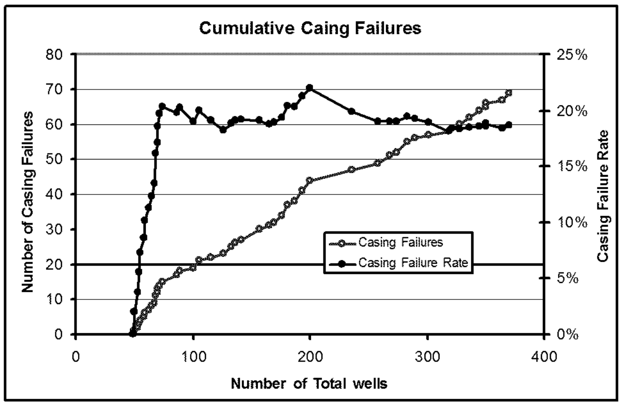

Fig. 1 Cumulative casing failures in Cymric 1Y project (before 2002).

Each of the casing failure occurred after 21 to 108 cycles of steam injections in Cymric 1Y project (Fig. 2).

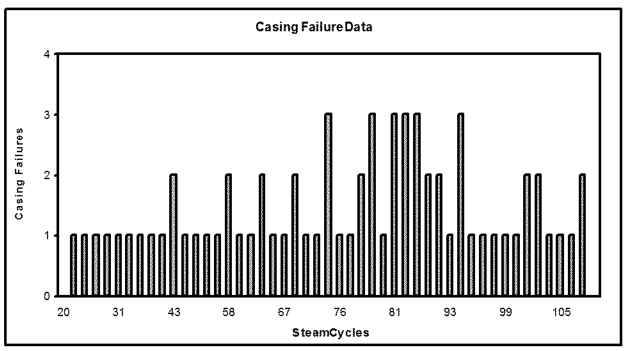

Fig. 2 Cymric 1Y casing failures vs. steam injection cycles (before 2002).

The casing failures can generally be classified as two major types or categories: (1) casing ID restriction, including casing collapse and buckling, and (2) casing parted, including casing hole and leak. The following Table 1 lists the number and percentage of each type of casing failure, from the failed 69 wells out of the total 370 wells.

Table 1. Cymric 1Y Casing Failures (before 2002)

Casing Failure Types	# of Failed Casing	% of Failures
ID restriction, collapse, buckling	29	42.03%
Parted, hole, leak	32	46.38%
Not sure which of above	8	11.59%
Total	69	100.00%

The casing data and cyclic steam injection operation data in Cymric 1Y project are listed as follows. The typical casing schematic and the casing failure locations (around surface casing shoe depth and perforation depth) observed in Cymric 1Y project are illustrated in Fig. 3.

- Surface casing: 10 ¾" casing, 40.5#/ft, K55, BTC @ 380 ft.
- Production casing: 7", 23# or 29#, L80, Hydril 563 @ 1500 ft.
- All cement top to surface. Foam cement used for production casing.
- Tubing: 2 7/8", 6.5#, L80, EUE. Packer or No packer.
- Perforation depth from 1100-1400 ft.
- Steam injection temperature ~550 deg. F, injection pressure ~ 1100 psi.
- 3200 Barrels steam injected over 60 hours.
- Soak time: 2 days
- Production rate 100 BOPD with 65% water cut. (285 BPD gross)
- Flow back pressures start at 700 psi and end around 250 psi.
- Flow back time of 20 days.
- Steam injection and oil production through tubing (puff and huff).

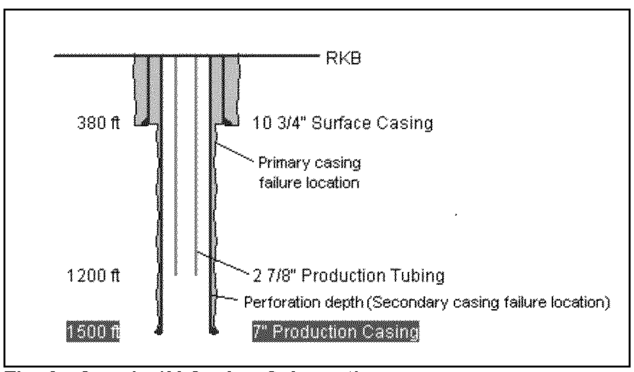

Fig. 3 Cymric 1Y Casing Schematic.

Casing Failure Analysis

1. Casing Hot-Yield

Casing temperature and thermal stress/strain are modeled for the cyclic steam injection operation in Cymric 1Y project to understand the casing failures. Fig. 4 presents the modeled casing temperature profiles for the three periods of cyclic steam injection operation (steam, soak, and production), with comparing with the initial casing temperature (the undisturbed formation temperature).

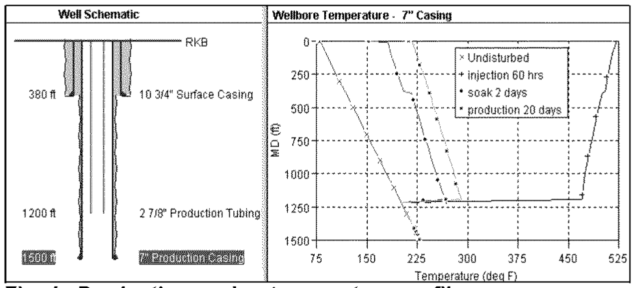

Fig. 4 Production casing temperature profiles.

The production casing temperature is seen to increase up to about 525 deg. F at the top of casing and up to about 475 deg. F at the bottom of casing in the steam injection period. The net casing temperature increase over the initial (undisturbed) temperature is then about 440 deg. F at the top of casing and about 260 deg. F at the bottom of casing. We know that an increase of casing temperature will induce a casing thermal compressive axial stress when the casing is fixed or restricted from thermal expansion in the casing longitudinal direction by cement and wellhead. The higher the casing temperature increases in steam injection period, the larger the induced casing thermal compressive axial stress is generated. Although the highest casing temperature increase is shown at the top of production casing, the casing failures were not observed there, but at around the surface casing shoe depth and perforation depth. The explanations may rely on two reasons: (1) casing thermal compressive axial stress at the top of casing may be less than that predicted by fixed-ends model, as casing may not be completed restricted at the top due to possible up-movement of surface formation from thermal axial expansion, and (2) cement and surface casing may provide a protection to the inside production casing section against formation lateral-movement from thermal radial expansion.

To the middle section of production casing, it can be considered completely restricted from thermal expansion in longitudinal direction, and the casing thermal compressive axial strain ($\Delta\varepsilon$) and stress ($\Delta\sigma$) due to the increase of casing temperature can be directly calculated by using casing thermal expansion coefficient (α), casing temperature increase (ΔT), and casing material Yong's modulus (E):[1]

$$\Delta\varepsilon = \alpha\Delta T \qquad (1)$$

$$\Delta\sigma = -\alpha E \Delta T \qquad (2)$$

For the production casing in Cymric 1Y project, the casing temperature increase is about 386 deg. F (from 119 deg. F of initial/undisturbed casing temperature to 505 deg. F at steam injection 60 hrs, as shown in Fig. 4) at the primary production casing failure location (around the surface casing shoe), and the casing thermal axial compressive stress is then calculated as

$$\Delta\sigma = -\ 6.9*10^{-6}*30*10^{6}*(505-119) = -\ 79{,}902 \text{ psi}$$

This thermal axial compressive stress exceeds the reduced casing yield strength (66,114 psi) at the corresponding temperature (505 deg. F) for the L-80 grade production casing, and can cause the production casing yield under the thermal axial compressive stress (hot-yield) at that location:[2]

$$\sigma_y \text{ (at 505 deg. F)} = 80{,}000*(1-(505-100)/2333.3) = 66{,}114 \text{ psi}$$

When the L-80 grade production casing in Cymric 1Y project is hot-yielded at the primary production casing failure location (around the surface casing shoe depth) under the thermal axial compressive stress in steam injection period, the casing resistance to collapse pressure should be significantly reduced and the casing could be easily collapsed by a small external pressure. The casing external pressure may come from annulus trapped pressure or casing-cement contact pressure from thermal radial expansions of casing and formation as temperature increases.[3] Casing-cement contact pressure induced from thermal radial expansions may also damage the cement and make casing collapse becomes even easier under a resultant non-uniform external pressure condition. Severe casing buckling and deformation may also occur once cement is damaged, when casing is under high thermal axial compressive load.

Figure 5 illustrates the hot-yield of the 7" production casing in Cymric 1Y project, where the triaxial safety factor is shown less than 1.0 for the top ~620 ft casing section and the casing loading line is located outside the casing VME yield ellipse for the same casing section. A small external pressure from annulus trapped pressure or casing-cement contact pressure by thermal radial expansions of casing and formation is therefore to collapse the casing as indicated. Although no casing hot-yield occurs at the secondary casing failure location (around the perforation depth ~1200 ft) by calculation, the observed casing failures at that location may be related to a possible damage of cement due to perforation, production, and casing-cement contact pressure by thermal radial expansions of casing and formation, causing casing buckling under thermal axial compressive load and casing collapse under non-uniform external pressure condition.

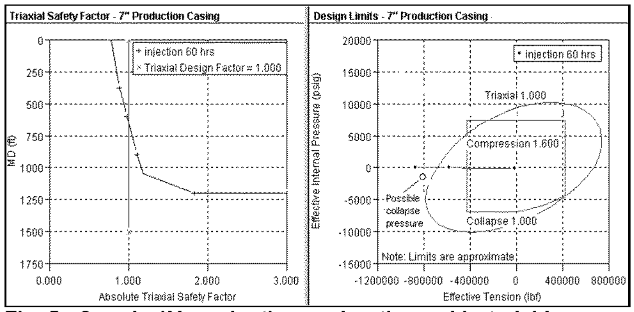

Fig. 5 Cymric 1Y production casing thermal hot-yield.

2. Casing Fatigue

Besides casing hot-yield and the resultant casing collapse failure, casing fatigue failure may also occur in cyclic steam-injection operation wells. We know that casing temperature increases in steam-injection period and reduces in the soak period in cyclic steam-injection operation, as shown in Fig. 4. Casing can be hot-yielded in thermal axial compression in steam-injection period and become under axial tensile stress in soak period, depending on the degree of casing temperature change in steam and soak periods. This alternation of casing axial compressive and tensile stresses can result in casing fatigue failure, especially at casing connection due to stress concentration.

For the cyclic steam-injection operation in Cymric 1Y project, the casing temperature at the primary production casing failure location (the surface casing shoe depth) is modeled to be about 505 deg. F at the end of steam-injection and about 209 deg. F at the end of soak, as shown in Fig. 4. The corresponding 7" production casing axial stress in the first cycle of steam injection is roughly illustrated in Fig. 6, where a perfect-plasticity of casing material is used to simplify the stress-strain relationship of steel casing plasticity. It is seen that casing pipe body is hot-yielded under thermal axial compressive stress in steam period, but does not develop axial tensile stress in soak period due to a relatively high soak temperature (209 deg. F). However, due to stress concentration, a local tensile yield is developed at casing connection (last pin thread) in soak period as shown in Fig. 6. The local hot-yield at the connection is also developed much earlier than on casing pipe body in the steam injection period due to stress concentration. On the subsequent cycles of steam injection operation, the local yielding at casing connection under compressive and tensile stresses will be repeated, and will result in casing fatigue failure at connection. This stress concentration effect may also be applied to any casing body imperfections and cause casing fatigue at such locations. A common stress concentration factor 3.50 at casing connection is used here to develop Fig. 6.

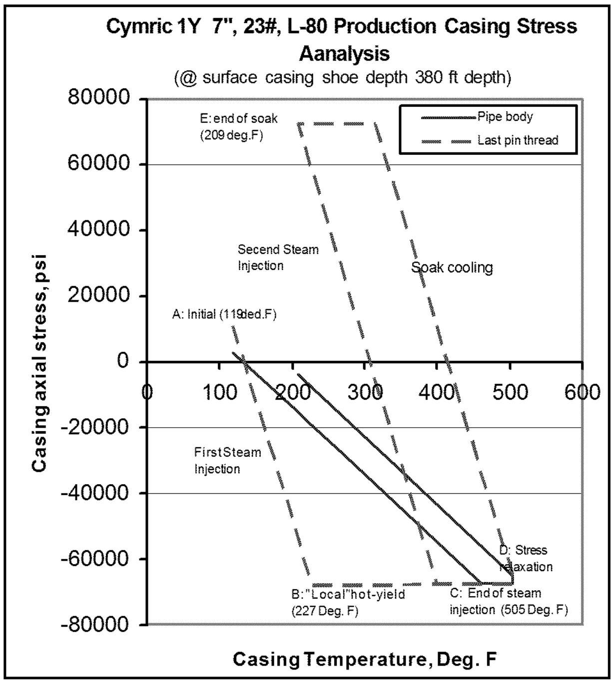

Fig. 6 Casing thermal stress profiles (stress concentration factor 3.50 at connection).

The local stress-strain response at casing connection due to stress concentration, different from the nominally induced casing pipe body thermal axial stress, is similar to what was pointed out in a metal fatigue textbook[4] on "notched" materials, as shown in Fig. 7, where the nominally applied stress (S) is all in tensile stress, while the local stress-strain (σ) response at the notch (hole) is completed reversed (tensile and compressive) due to residual stress developed as a result of local yielding at the notch root.

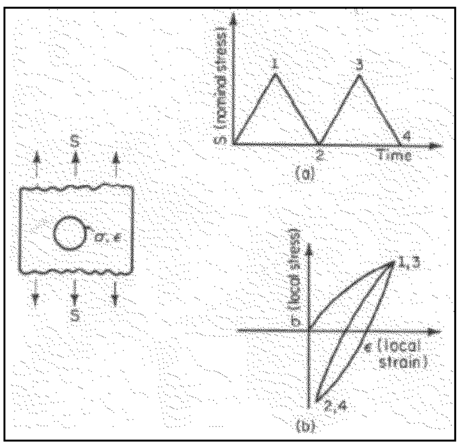

Fig. 7 Completed reversed local stress-strain response.[4]

There are generally three basic methods on fatigue analysis: (1) the stress-life method to determine the fatigue life of a smooth specimen subjected to an alternating stress. This method may also be used for high cycle fatigue of notch specimen where the notch strains are predominantly elastic. (2) the strain-life method which is developed to account for notch root plasticity and the influence of local sequence effects on local mean and residual stresses. (3) Fracture mechanics to account for fatigue crack growth at a notch, which allows estimation of the propagation portion of fatigue life. The strain-life method will be used in this paper to analyze casing fatigue at casing connection in cyclic steam-injection operation wells, as large plasticity at the connection (last pin thread) is seen in Fig. 6.

The following strain-life Manson equation[5] (Eq. 3) can be used to estimate the low-cycle fatigue life at casing connection in cyclic steam injection operation. It relates the fatigue life (cycles) to the total cyclic strain change, and simply indicates that the material properties of tensile strength (S_u), Young's modulus (E), and true fatigue strain (ε_f), which can be obtained from a monotonic tensile test, are the main variables to control the low-cycle fatigue.

$$\Delta\varepsilon_t = 3.5\frac{S_u}{E}(N)^{-0.12} + \varepsilon_f^{0.6}(N)^{-0.6} \qquad (3)$$

Figure 8 and 9 are the plotted strain-life curves developed by using Manson equation with varying material tensile strength (S_u) and true fatigue strain (ε_f) on L-80 grade of casing material. No significant change is however seen to the fatigue life on the plotted range of the variables, though casing material (grade) with good ductility (larger ε_f) and high strength (larger S_u) can have longer fatigue life.

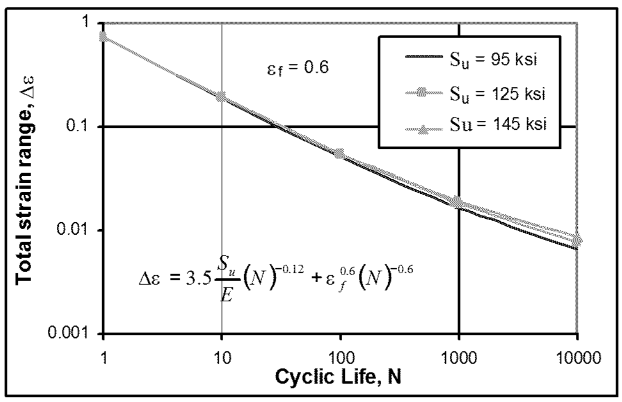

Fig. 8 Effect of material tensile strength on fatigue life.

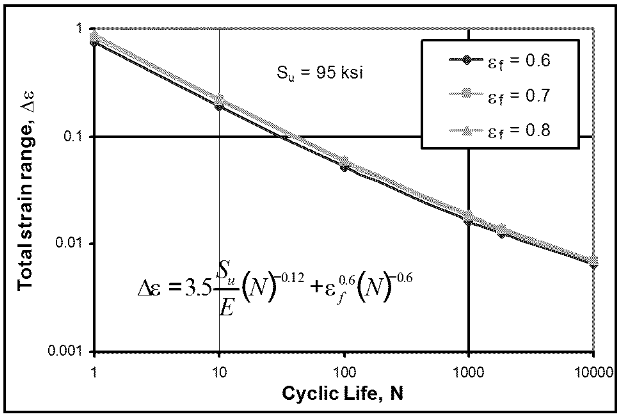

Fig. 9 Effect of true fatigue strain on fatigue life.

Now, we need to determine the local cyclic strain change at the casing connection in cyclic steam injection operation, and then use the Manson equation to predict casing fatigue at connection. Generally, the total cyclic strain change may be obtained from (1) Strain gage measurements, (2) Finite element analysis, and (3) Methods that relates local stress and strain to nominal values. We will use the third approach to estimate local cyclic strain change at the casing connection in this paper.

For cyclic steam-injection operation, the cyclic nominal strain on casing pipe body can be estimated directly by the casing temperature change between steam injection and soak periods. As shown in Fig. 6 for the Cymric 1Y project, the casing temperature change at the primary casing failure location is roughly between 505 deg. F at steam injection and 209 deg. F at soak, and the cyclic nominal strain on casing pipe body can then be estimated as

$$\Delta\varepsilon_p = -\,6.9*10^{-6}*(209 - 505)*3.5 = 0.002$$

If we directly apply the stress concentration factor to this cyclic nominal strain on casing pipe body to estimate the total cyclic strain change at casing connection, we will not get the correct value on the total cyclic strain change at casing connection due to the thread (notch) root plasticity. The theoretical stress concentration factor (K_t), used to relate the nominal stress (S) to the local stress (σ) and the nominal strain (e) to local strain (ε), remains constant until yield begins. Upon yielding ($\sigma/\sigma_y > 1$), the local stress (σ) and local strain (ε) are no longer related to the nominal values by theoretical stress concentration factor K_t. Instead, local values are related to the nominal values in terms of stress and strain concentration factors, where the stress concentration factor K_σ decreases with respect to K_t and the strain concentration factor K_ε increases respect to K_t, as shown in Fig. 10.

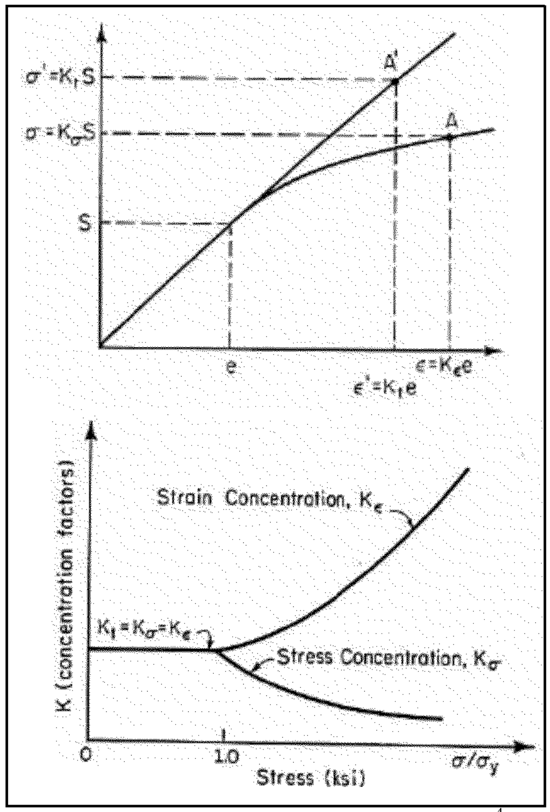

Fig. 10 Stress and strain concentration factors.[4]

Therefore, as the plastic yielding occurs at casing connection (last pin thread) in the cyclic steam injection operation at the Cymric 1Y project (Fig. 6), the total cyclic strain change at casing connection ($\Delta\varepsilon_t$) will be larger than the product of the theoretical stress concentration factor K_t and the thermal strain change on casing pipe body $\Delta\varepsilon_p$ (based on 505 deg. F at steam injection and 209 deg. F at soak):

$$\Delta\varepsilon_t > K_t\Delta\varepsilon_p = -\,6.9*10^{-6}*(209 - 505)*3.5 = 0.007$$

The total cyclic strain change at casing connection (last pin thread) may be more accurately modeled through Finite Element Analysis (FEA), or estimated through notch stress-strain behavior equations, such as the following Eqs. 4 and 5 developed by elastic-plastic form of Neuber's rule[4], that relates the change of local stress ($\Delta\sigma_t$) and strain ($\Delta\varepsilon_t$) to the nominal values:

$$\Delta\varepsilon_t = \frac{\Delta\sigma_t}{E} + 2\left(\frac{\Delta\sigma_t}{2K'}\right)^{1/n'} \quad (4)$$

$$\frac{(K_f \Delta S_t)^2}{2E} = \frac{(\Delta\sigma_t)^2}{2E} + \Delta\sigma_t\left(\frac{\Delta\sigma_t}{2K'}\right)^{1/n'} \quad (5)$$

For the L-80 grade casing used in Cymric 1Y project, casing material cyclic strength coefficient (K') and cyclic strain hardening exponent (n') in the above notch stress-strain behavior equations are estimated as 155,700 psi and 0.14, by the following correlations:[4]

$$K' = \frac{\sigma'_f}{\left(\varepsilon'_f\right)^{n'}} \qquad (6)$$

$$n' = \frac{b}{c} \qquad (7)$$

With b = -0.085, c = -0.6, $\sigma'_f = S_u + 50$ psi, $S_u = 95$ psi, and $\varepsilon'_f = 0.6$.

The total cyclic change of local stress ($\Delta\sigma_t$) and strain ($\Delta\varepsilon_t$) at the connection (last pin thread) at the primary casing failure location in Cymric 1Y project can then be calculated out from Eqs. 4 and 5, with the total cyclic change nominal stress at casing pipe body $\Delta S = 62{,}000$ psi (from Fig. 6), casing Young's modulus E = 30,000,000 psi, casing connection fatigue notch factor $K_f = 3.5$, casing material cyclic strength coefficient K' = 155,700 psi, and cyclic strain hardening exponent n' = 0.14:

$$\Delta\sigma_t = 152{,}100 \text{ psi}$$

$$\Delta\varepsilon_t = 0.017$$

Using the strain-life Manson equation (Eq. 3) with S_u = 95,000 psi, E=30,000,000 psi, $\varepsilon_f = 0.60$, a fatigue life of about 930 (cycles) is predicted, for L-80 grade casing to the estimated total cyclic change of local strain $\Delta\varepsilon_t = 0.017$.

This predicted fatigue life (930 cycles) is higher than what was observed in the Cymric 1Y project (about 80 cycles, Fig. 2), which may be due to some factors that would increase the total cyclic change of local strain at casing connection and/or body imperfections, such as casing buckling and/or a higher casing connection fatigue notch factor K_f, are not considered in the above analysis. If the total cyclic change of local strain at casing connection would be increased to 0.053, the L-80 grade production casing fatigue life would be predicted by Manson equation (Eq. 3) at only 100 cycles of steam injection operation under Cymric 1Y project condition.

Recommendations and Conclusion

From modeling casing temperature and analyzing casing thermal stress/strain, hot-yield, and casing fatigue in steam injection wells, the following conclusions may be drawn regarding casing design in steam injection wells:

1. Production casing is usually hot-yielded in steam injection wells due to high thermal axial compressive stress. Casing collapse resistance reduces when casing hot-yielded and casing can easily be collapsed under small external pressure, which can be present as annulus trapped pressure and/or casing-cement contact pressure from thermal radial expansions of casing and formation at steam injection period. Higher strength grade casing (such as 110 grade) may be used to help reduce casing hot-yield and the related casing collapse failure. The use of P-110 grade production casing in Cymric 1Y project after 2002 has shown a significant reduction of casing failures.
2. Casing failure can also occur by fatigue in cyclic steam injection wells at casing connection (last pin thread) and casing pipe body imperfections with stress/strain concentration, due to the local axial thermal compressive and tensile stress/strain alternation between steam and soak periods. Casing material (grade) with good ductility and high strength needs to be used for a better (longer) fatigue life, as shown by Fig. 8 and 9 (the higher the material true fatigue strain ε_f and the material tensile strength S_u, the longer the fatigue life of casing).
3. Setting deeper surface casing may help reduce production casing failure in steam injection wells, as it can reduce the production casing temperature elevation and then casing hot-yield and the related collapse failure near the surface casing depth location. It can also reduce the production casing temperature alternation and then the total local strain change and the related fatigue failure near the surface casing depth location in cyclic steam injection operation.
4. Further investigation may be needed on the effect of casing buckling on casing fatigue in cyclic steam injection wells.

Nomenclature

b = Fatigue strength exponent,
c = Fatigue ductile exponent,
e = Nominal strain
E = Casing Young's modulus, 30,000,000 psi for steel
K_f = Casing connection fatigue notch factor,
K_t = Casing connection stress-strain concentration factor
K_σ = Casing connection stress concentration factor,
K_ε = Casing connection strain concentration factor,
K' = Casing material cyclic strength coefficient, psi
n' = Cyclic strain hardening exponent
N = Number of stress/strain cycle
S = Nominal stress, psi
S_u = Casing tensile strength, psi
ΔS_t = Total cyclic change of nominal stress, psi
ΔT = casing temperature increase, Deg. F
α = Casing thermal expansion coefficient, 0.0000069/deg. F for steel

σ = Local stress, psi
σ'_f = Casing fatigue strength coefficient, psi
σ_y = Casing yield strength, psi
$\Delta\sigma$ = Casing thermal axial stress, psi
$\Delta\sigma_t$ = Total cyclic change of local stress, psi
ε = Local strain
ε_f = True fatigue strain
ε'_f = Fatigue ductile coefficient
$\Delta\varepsilon$ = Casing thermal axial strain
$\Delta\varepsilon_p$ = Total cyclic change of nominal strain
$\Delta\varepsilon_t$ = Total cyclic change of local strain

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